Size matters: How single-species management can contribute to ecosystem-based fisheries management

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Abstract

In this study we show how substantial gains towards the goals of ecosystem-based fisheries management (EBFM) can be achieved by different single-species management. We show that fishing has much less impact on stocks if fish are caught after they have reached the size (L_{opt}) where growth rate and cohort biomass are maximum. To demonstrate our point we compare the impact of three fishing scenarios on 9 stocks from the North Sea and the Baltic. Scenario (1) is the current fishing regime, scenario (2) is a new management regime proposed by the European Commission, aiming for maximum sustainable yield obtained from all stocks, and scenario (3) is set so that it achieves the same yield as scenario (2), albeit with fishing on sizes beyond L_{opt}. Results show that scenarios (2) and (3) are significant improvements compared to current fishing practice. However, scenario (3) consistently shows least impact on the stocks, with seven-fold higher biomass of demersal fishes and an age structure similar to an unfished stock. This allows juveniles and adults to better fulfil their ecological roles, a major step towards the goals of ecosystem-based fisheries management. We give examples where scenario (3) is practiced in successful fisheries. We present a new interpretation of the relative yield per recruit isopleth diagram with indication of a new target area for fisheries operating within the context of EBFM. We present a new expression of the relative biomass per recruit isopleth diagram, which supports our analysis. We conclude that size matters for precautionary and ecosystem-based fisheries management and present a list of additional advantages associated with fishing at L_{opt}.
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1. Introduction

There is wide agreement that fisheries must be managed in the context of the overall state of the respective ecosystem and with least possible impact on stocks, habitats, food webs and non-target species (Jennings and Kaiser, 1998; Murawski, 2000; Lotze, 2004; Frid et al., 2005). This has been termed ecosystem-based fisheries management (EBFM), with the goal of sustaining healthy marine ecosystems and the fisheries they support (Brodziak and Link, 2002; Pikitch et al., 2004). Some specific goals of EBFM include sustaining fishery productivity, maintaining community diversity, and maintaining a healthy trophic structure (food web) (Brodziak and Link, 2002). There is a general perception that successful EBFM will need new

sophisticated models and indicator matrices to inform managers about the best actions to take (Jennings and Kaiser, 1998; Latour et al., 2003; Tudela and Short, 2005). Such new approaches are to incorporate productivity and mortality of the various species, predator–prey interactions, competition, carrying capacities, and variability in population specific and environmental parameters (Fulton et al., 2003; Walters et al., 2004). However, there are also critical voices such as Valdimarsson and Metzner (2005) who ask: "Indeed, if we are failing to achieve the basic requirement of encouraging fishers to leave enough fish in the water for future sustainable harvests, how can we hope that an even more sophisticated system will work?" Additionally, even the most well-studied ecosystems, such as Georges Bank still lack sufficient data to fully apply some suggested EBFM approaches (Brodziak and Link, 2002). This gap between EBFM theory and applicability in a management context is preventing EBFM from functioning to improve the condition of our oceans. In fact, despite increased efforts to improve management through better

Table 1
Relevant lengths of commercial fishes in the North Sea (NS), Western (WB) and Eastern Baltic (EB)

Species	Area	L_L	L_m	L_{opt}
Cod, *Gadus morhua*, Gadidae	NS	35	61	86
Cod, *Gadus morhua*, Gadidae	WB	35[a]	43	80
Haddock, *Melanogrammus aeglefinus*, Gadidae	NS	30	29	49
Whiting, *Merlangius merlangus*, Gadidae	NS	27	25	37
Saithe, *Pollachius virens*, Gadidae	NS	35	58	118
Plaice, *Pleuronectes platessa*, Pleuronectidae	NS	27	25	46
Herring, *Clupea harengus*, Clupeidae	NS	20	22	24
Herring, *Clupea harengus*, Clupeidae	EB	11	20	20
Sprat, *Sprattus sprattus*, Clupeidae	EB	–	8	10

L_L is the legal length, L_m is the length where 50% of specimens become mature, and L_{opt} is the length where unfished cohorts reach maximum biomass.

[a] In January 2006 the minimum legal size for Baltic Cod was raised to 38 cm.

science, the number of overfished or collapsed stocks continues to increase (Worm et al., 2006). This is especially striking in Europe, where more stocks than ever before are outside safe biological limits (Frid et al., 2005; ICES, 2005a; Garcia and De Leiva Moreno, 2005) and the North Sea Cod (*Gadus morhua*: Gadidae) is in danger of collapse. Under current European fisheries management, most fish are taken as soon as they can be caught and the market is willing to accept them. This is reflected in the legal minimum landing sizes for major commercial species (see Table 1), which show no consistent relationship to meaningful target sizes, such as size at first maturity (L_m) or the size where full usage of the population growth potential is made (L_{opt}, see below). To make matters worse, legal mesh sizes prescribed in EU waters are so small, that they catch substantial amounts of fish below legal size. For example, the EU 2000 trawl net, used to catch Cod, Haddock (*Melanogrammus aeglefinus*: Gadidae) and Whiting (*Merlangius merlangus*: Gadidae) in the North Sea, has a mesh size which retains 50% of fish at 25 cm in length (ICES, 2003). A comparison with lengths stated in Table 1 makes it clear that this trawl catches juveniles of all three species, especially Haddock and Cod. More importantly, it catches substantial numbers of fishes below legal minimum landing size, forcing fishers to discard this catch at sea.

The discrepancy between legal minimum size and size at maturity is strongest for North Sea Cod, resulting in severe recruitment overfishing. The stock has declined so much that for years fishers have been unable to take the total allowable catch (TAC) set by EC management (ICES, 2005b). Note that this TAC always exceeded the levels recommended by the International Council for the Exploration of the Seas (ICES), the official scientific advisory body of the European Commission, to the point where ICES recommended a complete closure of the Cod fishery and the EC continued issuing 'more-than-could-be caught' TACs, *de facto* legalizing unlimited fishing effort on a stock in danger of collapse.

The regular non-implementation of the scientific advice also has negative effects on science and scientists. With regard to science, the overruling of catch limits means that there is no feedback loop as to the appropriateness of the recommended TACs. Any observed negative development of the stock could have been caused by the TAC increase alone. With regard to

the scientists, the fact that their recommendations are not implemented relieves them of any responsibility for the status of the stocks. These effects also spill over into the public seeing fisheries management institutions as lacking legitimacy (Nielsen et al., 2001)—doing lots of work but achieving no results.

There is a widespread perception that maintaining healthy fish stocks will require considerably less exploitation (ICES, 2005a) and lower catches. In this article we want to show how substantial gains towards the goals of EBFM can be achieved through different single-species management, and that, in time, this can be done without drastic changes in current catch levels (Radtke, 2003). We explore the impacts of three different fishing scenarios on 9 fish stocks of the North Sea and the Baltic with regards to the survival of first-time spawners, survival to the size where growth in weight and cohort biomass are maximum, and survival of large spawners. The first scenario is the current fishing regime as reconstructed from respective ICES stock assessment reports. The second scenario (EC-MSY) is a new management regime suggested by the European Commission, which aims for fishing all stocks at maximum sustainable yield (European Commission, 2006a). The third scenario (L_{opt}) is an alternative regime where the same catch as obtained under EC-MSY is taken after growth in weight and cohort biomass have reached their maximum.

2. Materials and methods

2.1. Parameters

We used catch-at-age analysis data on the North Sea and Baltic stocks as published by ICES (ICES, 2005b,c,d,e). For the purpose of this study, we took for every stock the mean of initial number of individuals (R = recruits) of three subsequent cohorts which entered the fishery in the 1990s and attained their maximum assessed age between 2000 and 2004. We also took the mean fishing mortality (F) indicated for the fully exploited phase. For the EC-MSY fishing scenario we used fishing mortalities given as $F_{0.1}$ by the European Commission (2006b), except for Herring where we used $F_{max} = 0.41$ and 0.53 for the North Sea and Baltic, respectively, given in the same document, because $F_{0.1} = 0.13$ and 0.23 resulted in unrealistically low MSY yields.

We used length–weight relationships from FishBase (www.fishbase.org, Froese and Pauly, 2000) for converting mean length into mean weight. We used published von Bertalanffy growth parameters as indicated in Table 2.

Lengths at 50% maturity were obtained from stock-specific ogives provided by ICES (ICES, 2005b,c,d,e) and converting age into the corresponding length, using the von Bertalanffy growth function (VBGF).

All parameters used for the different stocks are shown in Table 2.

2.2. Calculation of cohort biomass-at-length

For each of the three scenarios defined above, cohort biomass was calculated as a function of the mean length of fishes. First,

Table 2
Parameters used for comparing fishing scenarios, with area NS, North Sea; WB, Western Baltic (includes ICES areas 25–29 and 32)

Species	Area	L_{inf} (cm)	K (year^{-1})	t_0 (years)	a	b	t_r	R	M	F_{cur}	$F_{EC\text{-}MSY}$	F_{Lopt}	Reference
Cod	NS	129.1	0.14	−0.82	0.0104	3.0	2	141,266	0.21	0.93	0.13	0.12	ICES (2005b); Winker (2005)
Cod	WB	120.0	0.13	−0.90	0.0104	3.0	2	40,307	0.20	1.18	0.15	0.12	Draganik and Netzel (1966); ICES (2005b)
Haddock	NS	73.5	0.15	−0.83	0.0052	3.2	2	555,833	0.23	0.93	0.20	0.13	ICES (2005b); Winker (2005)
Whiting	NS	55.4	0.23	−0.62	0.0075	3.0	2	498,635	0.35	0.61	0.27	0.28	ICES (2005b); Winker (2005)
Saithe	NS	177.0	0.07	−1.10	0.0077	3.0	3	145,362	0.11	0.51	0.11	0.07	Jennings and Kaiser (1998); ICES (2005b)
Plaice	NS	68.5	0.10	−1.45	0.0103	3.0	3	293,331	0.15	0.71	0.12	0.10	Bannister (1978); ICES (2005b)
Herring	NS	33.3	0.29	−1.60	0.0075	3.0	2	3,130,000	0.44	0.46	0.41	0.37	Hubold (1975); ICES (2005e)
Herring	WB	29.7	0.28	−1.97	0.0075	3.0	1	3,316,800	0.41	0.47	0.53	0.57	Rechlin (1986)
Sprat	WB	14.4	0.30	−0.68	0.0041	3.2	2	106,119,767	0.45	0.36	0.52	0.52	(Rechlin, 1974; ICES, 2005e)

L_{inf}, K and t_0 are parameters of the VBGF; a and b are parameters of the length–weight relationship; R is the number of recruits in thousands at t_r; M is the natural mortality for the exploited phase and F_{Lopt} is the fishing mortality needed to obtain the same yield as $Y_{EC\text{-}MSY}$ when fishing starts after L_{opt}. References refer to initial R and age, F_{cur}, and VBGF.

an age t was associated with each length L, using the rearranged form of the VBGF:

$$t = t_0 - \frac{1}{K} \ln\left(1 - \frac{L}{L_\infty}\right) \tag{1}$$

where: L_∞, K and t_0 are VBGF parameters (see Table 2).

Eq. (1) was also used to estimate the age of first catch t_c, related to each scenario. For the current and the EC-MSY scenarios, the related length at first catch was assumed equal to the present legal length L_l (see Table 1). For the L_{opt} scenario, a value of $L = L_{opt}$ was considered, based on Beverton and Holt (1957) and Beverton (1992):

$$L_{opt} = L_\infty \frac{3}{3 + (M/K)} \tag{2}$$

where L_{opt} is the length where the biomass of an unfished cohort reaches its maximum, and M is the instantaneous rate of natural mortality.

Then, we calculated number-at-age $N(t)$ in the cohort based on:

$$\begin{aligned} N_t &= R \cdot e^{-M(t-t_0)} \quad \text{for } t < t_c \\ N_t &= R \cdot e^{-M(t_c-t_0)} \cdot e^{-(M+F)(t-t_c)} \quad \text{for } t \geq t_c \end{aligned} \tag{3}$$

where R is the number of recruits (see Table 2), and F the fishing mortality related to the considered scenarios, F_{cur}, $F_{EC\text{-}MSY}$ and F_{Lopt}. F_{Lopt} was estimated iteratively as the value of F that generated a total catch equal to that obtained under the EC-MSY fishing scenario.

Finally, biomass-at-age $B(t)$ was estimated as the product of number $N(t)$ and mean weight $W(t)$ obtained from the respective length–weight relationship. These calculations were done for all ages over the entire length range, and thus biomass $B(t)$ could be plotted as a function of length. This method was applied to all stocks, and we derived from it the biomass of three categories of fishes: first-time spawners with $L = L_m$, spawners at optimum length with $L = L_{opt}$, and large spawners which for the purpose of this study were assigned arbitrarily a length of $L = L_{opt} + 0.1 L_{opt}$.

2.3. Calculation of yield

For all fishing scenarios and all stocks, we used Baranov's catch equation (Ricker, 1975) to obtain catch in numbers at age:

$$C_t = N_t F \frac{1 - e^{-Z}}{Z} \tag{4}$$

where C_t is the annual catch in numbers at age t, N_t is the number at the beginning of the year estimated from Eq. (3), F is the rate of fishing mortality and $Z = M + F$ is the total mortality rate. The catch in numbers was multiplied with the mean weight to obtain yield. Total yields produced by a cohort were obtained as sum of annual yields.

2.4. Calculation of yield and biomass per recruit

We used the equation for relative yield per recruit Y'/R as a function of relative size L_c/L_∞, exploitation rate $E = F/Z$ and the ratio between natural mortality M and von Bertalanffy growth parameter K (Beverton and Holt, 1966, Eq. (A3) in Appendix A). For the purpose of plotting several stocks in one Y'/R graph, we assumed a mean M/K ratio of 1.5, resulting in $L_{opt}/L_\infty = 0.67$ for all stocks (Jensen, 1996). Thus, the same Y'/R isopleths and L_{opt} line could be applied to several stocks and fishing scenarios, providing a synthesized overview of impact of size and fishing effort on yields. Additionally, we show Beverton and Holt's (1957) "eumetric" lines joining the vertical and horizontal tangents to Y'/R isopleths, respectively. The upper line shows the minimum exploitation rate needed for a given yield per recruit. The lower line shows the minimum size at first capture for a given yield per recruit. The area between the lines is the target of traditional fisheries management.

Isopleths of relative biomass per recruit B'/R were calculated to illustrate the impact of the various scenarios on the stock abundance. The equation usually used to calculate the 'weight of the commercial population' (Ricker, 1975) relates only to the exploited part of the stock, resulting in nearly vertical isopleths of relative biomass and suggesting negligible impact of size at first capture on cohort biomass, which is misleading because

cohort biomass is increasing with size at first capture. We used biomass per recruit instead of spawning biomass per recruit to be independent of assumptions on the size and age at first maturity. Also, we used relative biomass per recruit to simplify the demands on input parameters (L_c/L_∞ instead of t_c and F/Z instead of F). This then allowed us to plot different species in the same relative biomass per recruit graph. Since we did not find a suitable length-based equation for relative biomass in the literature a new equation was derived as shown in Appendix A.

2.5. Calculation of length at maximum growth rate

The von Bertalanffy growth function in weight has an inflection point at $0.296\,W_\infty$ where the growth rate dW/dt is maximum. Growth in length does not have an inflection, but the length corresponding $0.296W_\infty$ can be obtained from the following consideration: from the weight–length relationship for isometric growth we obtain $W_\infty = a\,L_\infty^3$ and $a = W_\infty/L_\infty^3$. For length at $0.296W_\infty$ we can now write

$$0.296W_\infty = \frac{W_\infty}{L_\infty^3}(xL_\infty)^3 \qquad (5)$$

Solving Eq. (5) for x gives the length at maximum growth in weight as $0.67L_\infty$, i.e., the same as L_{opt} when the M/K ratio in Eq. (2) is 1.5, see above.

3. Results

3.1. Size overfishing of North Sea Cod

The graph of cohort biomass expressed as a function of mean length (Fig. 1) provides insight into the mismanagement of the North Sea Cod and the inability of fishers to fish out their quotas. The u-shaped thin line indicates the percentage of the unfished cohort biomass that needs to be caught to achieve 139,026 t, i.e., the mean yield that was obtained in 1992–1994 from the three cohorts under consideration. As can be seen, this catch exceeds 100% of cohort biomass if all fish were to be caught near the legal minimum size of $L_L = 35$ cm, explaining why fishers have had
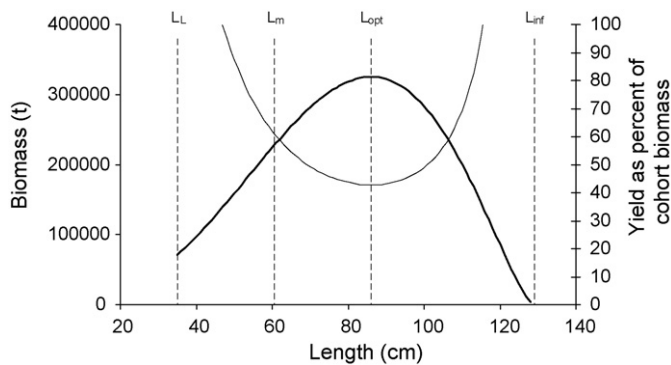

Fig. 1. *Gadus morhua*. Unfished cohort biomass (bold line) and respective percentage of the catch (thin line) of 139,026 t plotted over the mean length of the cohort, with indication of legal minimum length (L_L), length at first maturity (L_m), length at maximum biomass (L_{opt}) and asymptotic length (L_{inf}), for North Sea Cod.
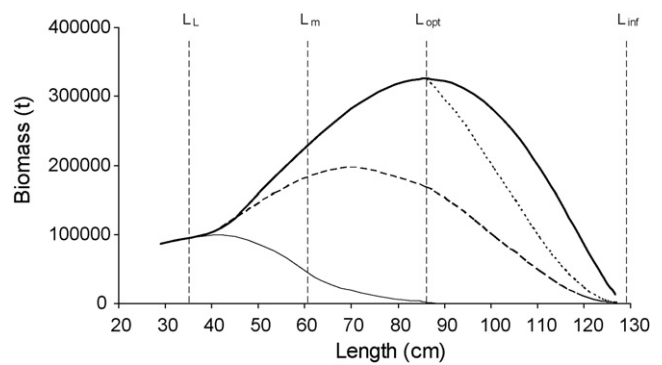

Fig. 2. *Gadus morhua*. North Sea Cod cohort biomass over mean length, with no exploitation (bold line), biomass with catch of 182,198 t only after L_{opt} (dotted line), biomass with same catch under EC-MSY scenario (dashed line), and current cohort biomass with current catch of 128,138 t (thin line). Vertical lines indicate current legal landing size (L_L), size at first maturity (L_m), optimum size (L_{opt}), and maximum size reached (L_{inf}).

difficulties fishing out their quotas with mean sizes in the catch near the legal minimum. However, the catch amounts to only 42% of the cohort biomass if most fish had been caught near the size where cohort biomass reaches a maximum. Unfortunately, almost no fish of this size survive current fishing (Fig. 2).

3.2. Comparing the three scenarios: effects on yield and size structure

The yields obtained under the EC-MSY fishing scenario were about the same as current yields for herring and sprat, but were on average 38% higher for demersal fishes, including increases of 21% for North Sea and 32% for Baltic Cod (Fig. 3). For Whiting the EC-MSY yield was lower than under the current scenario because $F_{0.1}$ instead of F_{max} values were used. For North Sea Herring EC-MSY yield was lower despite the use of F_{max}, but the difference (-4%) was small.
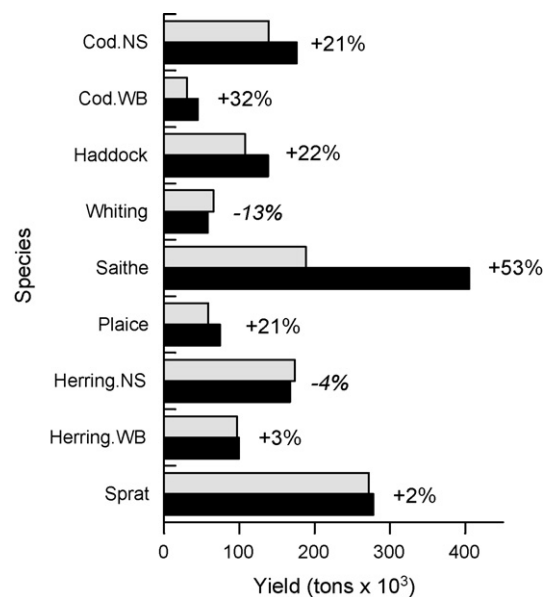

Fig. 3. Yields under the current (gray) and EC-MSY = L_{opt} (black) fishing scenarios with indication of the increase in yield under the EC-MSY scenario.
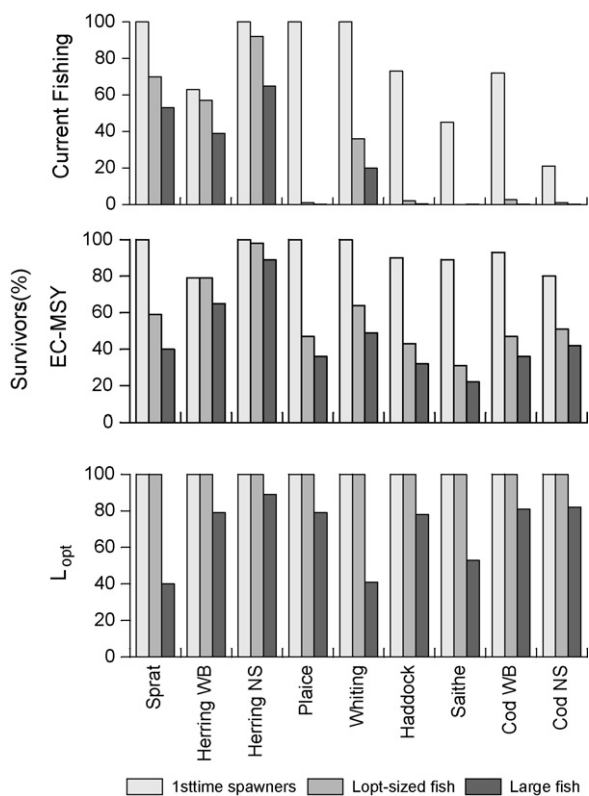
Fig. 4. Percentage of surviving first-time spawners, spawners at L_{opt}, and large spawners, for nine stocks under three different fishing scenarios: current, EC-MSY and L_{opt} fishing (bottom).

To reach these gains, fishing mortality had to be decreased on average by 78%, including a decrease of 87 and 86% for Baltic and North Sea Cod, respectively (Table 2). Given that the size at first capture is not changed in the EC-MSY scenario, this reduction has to be solely achieved by reducing fishing effort. In comparison, in the L_{opt} scenario much of the reduction in fishing mortality is achieved by catching few large instead of many small fishes, see example for North Sea Cod in the discussion.

The impact of the three fishing scenarios on first-time spawners, specimens at optimum length and large spawners is strikingly different (Fig. 4). Under the current fishing scenario, North Sea Cod has the lowest percentage (21%) of surviving first-time spawners, or put differently, 79% of the specimens in the current catch are juveniles. Percentages of surviving first-time spawners for the other stocks range from 45 to 100%. Large spawners are severely depleted (<1%) in Cod, Haddock, Saithe and Plaice and range from 12 to 65% for the other stocks. EC-MSY and L_{opt} fishing scenarios strongly increase the percentages of surviving first-time spawners for North Sea Cod, and also strongly increase the percentages of surviving L_{opt} spawners for all stocks. As a result of catching mostly large fishes, the L_{opt} scenario shows better survival in this group (mean 69%) than the EC-MSY scenario (mean 46%).

3.3. Effects on yield and biomass per recruit

Fig. 5 shows isopleth diagrams of relative yield and biomass per recruit as a function of exploitation rate and relative length

at first capture, with indication of the selected demersal stocks under the three different fishing scenarios. The graphs are vertically subdivided into two halves, with exploitation rates of $E > 0.5$ on the right side indicating overfishing (Gulland, 1971). They are horizontally subdivided into three sections for the juvenile phase, main reproductive phase, and large spawners phase. The L_{opt} line indicates where a given catch would have the least impact on the stock with regard to the fraction of biomass or individuals killed by fishing. This is illustrated by the Y'/R and B'/R isopleths being nearly parallel at and above the L_{opt} line.

All current demersal fisheries reside in the lower right quarter of the graphs, with overfishing of mostly juveniles and first-time spawners and very low biomass per recruit (about 10% of unfished biomass). Only Whiting falls within the area where maximum yield per recruit is obtained. The EC-MSY scenario aims for a strong reduction in fishing effort but no modification for the age or length of first capture. Under this scenario, stocks are moved into the maximum yield per recruit area (lower arrow in Fig. 5) and impact on biomass and age structure is somewhat reduced because of reduced effort. However, fishing of juveniles continues, resulting in a distorted age structure and more impact on the stocks than needed to obtain the respective yields. Conversely, under the L_{opt} scenario with similar yields as EC-MSY, fishing only starts towards the end of the main reproductive phase with the least possible impact on cohort biomass (~70% of unfished) and size structure (upper arrow in Fig. 5).

The key point here is that the three scenarios have clearly distinct impacts on demersal fishes. The L_{opt} scenario represents a new management strategy that obtains MSY yields by applying precautionary single-species management in anticipation of ecosystem-based fisheries management, resulting in a seven-fold increase in biomass and an age structure similar to an unfished stock.

For small pelagics (Sprat and Herring, Fig. 6), the differences between the three fishing scenarios are less striking because current fishing was already close to EC-MSY and L_{opt} scenarios. However, the L_{opt} scenario clearly increases biomass per recruit, an important consideration for EBFM because these small pelagics are major forage species.

4. Discussion

We explored what gains towards EBFM can be achieved by improving current single-species management (see also Mace, 2001; Radtke, 2003; Hall and Mainprize, 2004; Frid et al., 2005). We relied on a very simple assumption: sustainable fisheries can take only part of what is replenished every year. Thus, one can imagine the fishery acting only on one incoming year class or cohort once it has reached a certain size. For the stocks examined we took the mean size in numbers of three actual cohorts as documented in stock assessment reports. We then let these cohorts gain in weight as they grew in length according to respective length–weight relationships, and decrease in numbers according to respective natural mortality rates. This led to unfished cohort biomass curves, which reach a maximum at the length called L_{opt}. We then compared the biomass and size structure of surviving cohort members after the impact of three fishing sce-
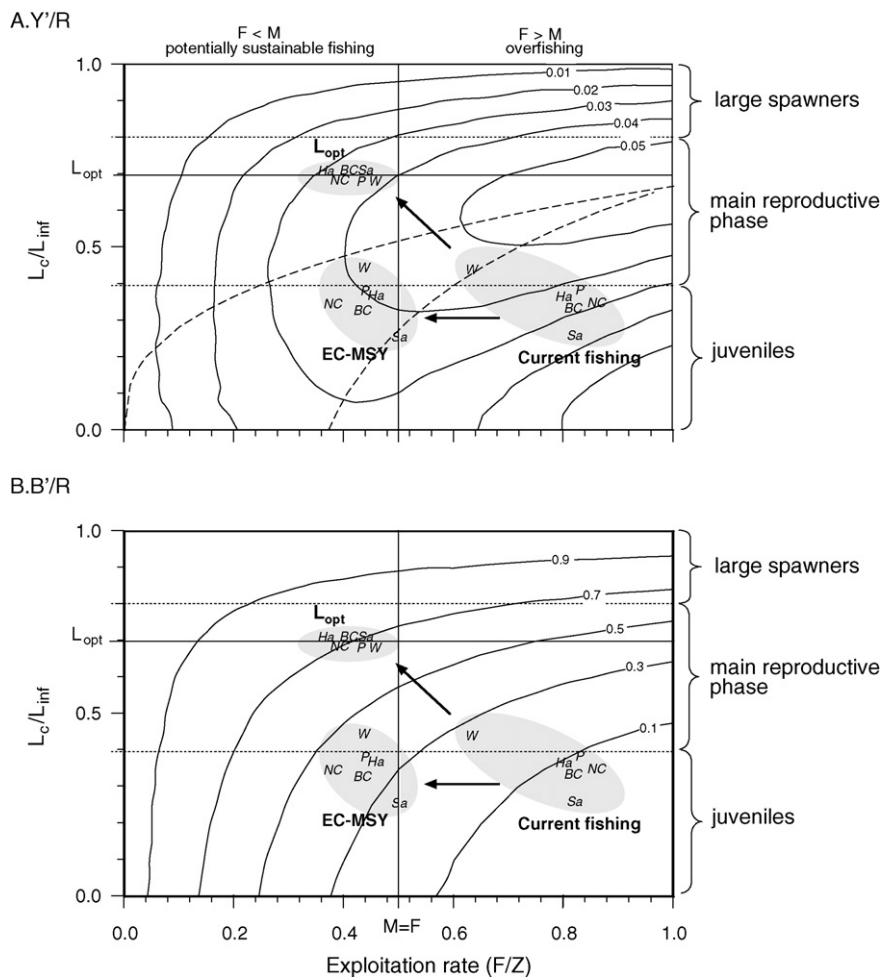
Fig. 5. Isopleth diagrams of (A) relative yield per recruit (Y'/R) and (B) relative biomass per recruit (B'/R) under the three scenarios as a function of relative size at first capture (L_c/L_{inf}) and exploitation rate ($E = F/Z$), for six demersal stocks in the North Sea and Baltic, where NC, North Sea Cod; BC, Baltic Cod; Ha, Haddock; W, Whiting; Sa, Saithe; P, Plaice. The numbers on the isopleths indicate relative yield and relative biomass per recruit, respectively. The upper dashed line in (A) represents the left-most points of the isopleths where the exploitation rate for a given relative yield is minimum. The lower dashed line marks the area of growth overfishing: to the right of this line a reduction in exploitation rate leads to an increase in relative yield.

narios which differed in the amount taken and the size at which fishing starts, everything else being equal.

We followed the fate of cohorts rather than populations under different fishing scenarios to avoid assumptions about recruitment. We took initial numbers of individuals from respective stock assessments instead of using fictitious numbers, in order to avoid an additional level of abstraction. Note that under the 'steady state' assumption, i.e., assuming negligible changes in size structure and recruitment, the curves in Figs. 1, 2 and 7 would represent the size structure of the population (Beverton and Holt, 1957; Allen, 1971). Over time, however, we would expect the different scenarios resulting in different recruitment patterns. We chose length rather than the more conventional age as *x*-axis in Figs. 1, 2 and 7 because size is what ultimately matters in fisheries, as it is more easily determined, communicated and controlled.

We do not claim that the parameters used (Table 2) or the modelled cohort biomasses and catches under the different scenarios are direct representations of what may have happened in the real world. However, because the same parameters and equa-

tions were used for the different scenarios, except for F and size at first capture, we assert that the trends and general conclusions based on this simple framework are correct.

Ecosystem-based fisheries management aiming to minimize impact on the stock and the ecosystem would strive to have the biomass curves of the exploited cohorts follow the curve of the unfished cohort as closely as possible. This is best achieved by the L_{opt} fishing scenario, which attains the same catch as the EC-MSY fishing scenario, albeit with fishing starting only after the cohort has reached its maximum biomass, and individuals have enjoyed maximum growth and have started reproduction (Fig. 2). Under the current fishing scenario only 80% of the sustainable catch is obtained and the size structure is strongly distorted, because fishing for juveniles kills relatively more fish resulting in fewer large fish. As pointed out by Ricker (1975), it is not so that many of the captured juvenile fish would have died anyway; the probability of dying from fishing (F) does not reduce the probability of dying from other causes (M), rather, these probabilities add up to total mortality ($Z = F + M$). For example, under the current fishing scenario for
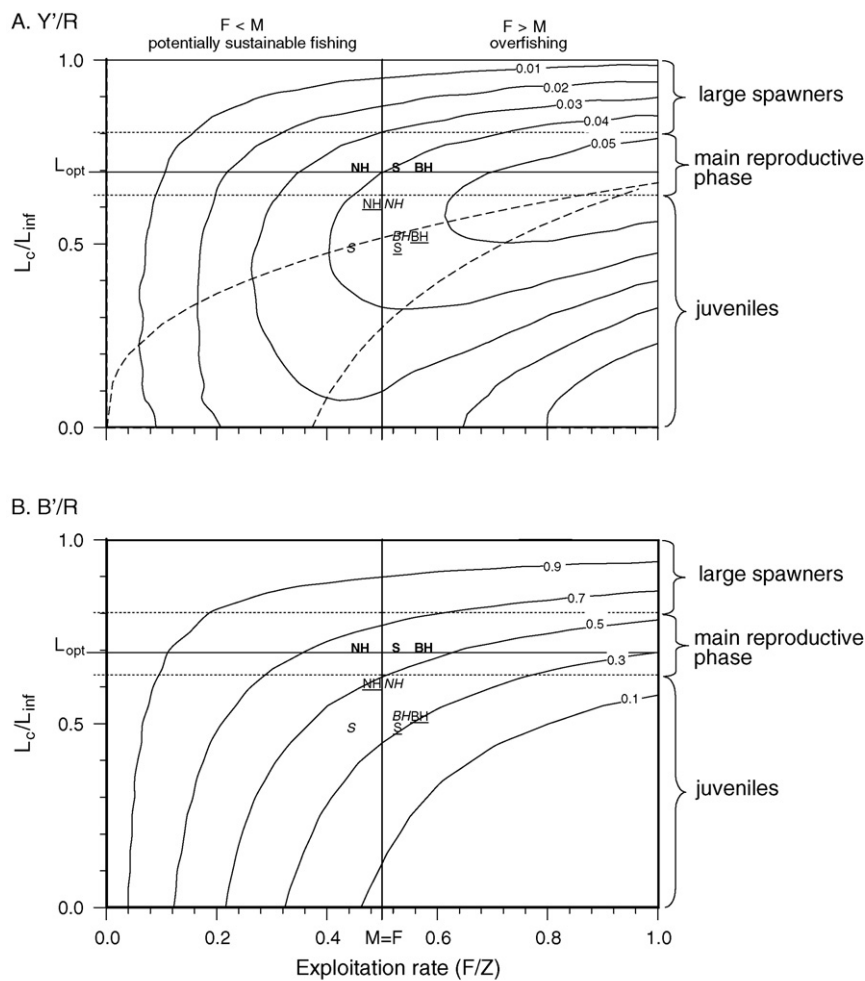
Fig. 6. Isopleth diagrams of (A) relative yield per recruit (Y'/R) and (B) relative biomass per recruit (B'/R) under the three scenarios as a function of relative size at first capture (L_c/L_∞) and exploitation rate ($E = F/Z$), for three stocks of small pelagics in the North Sea and Baltic, where NH, North Sea Herring; BH, Baltic Herring; S, Sprat. The current fishing regime is indicated with italics, EC-MSY with underline, and L_{opt} with boldface. The upper dashed line in (A) represents the left-most points of the isopleths where the exploitation rate for a given relative yield is minimum. The lower dashed line marks the area of growth overfishing: to the right of this line a reduction in exploitation rate leads to an increase in relative yield.
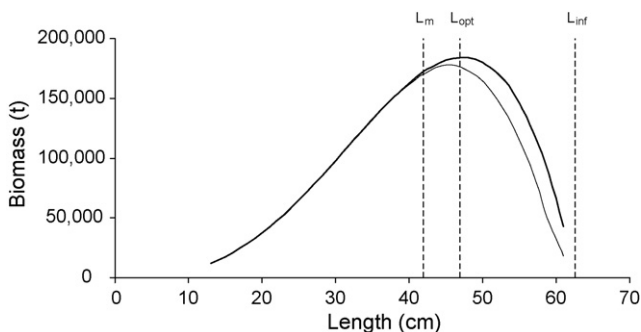

Fig. 7. *Theragra chalcogramma*. Cohort biomass over length, without fishing (bold line) and with fishing (thin line) for the Gulf of Alaska Pollock, with indication of length at first maturity (L_m), length at maximum cohort biomass (L_{opt}), and asymptotic length (L_∞). We used population dynamics data available for the year 2000 in Barbeaux et al. (2005) and VPA and catch-at-age data from Dorn et al. (2005).

North Sea Cod 115 million of mostly juvenile fish were killed to obtain 115,204 tonnes catch (829 fish/t), whereas under the L_{opt} scenario only 18 million fish were killed to obtain 139,026 t catch (102 fish/t). Fishing at L_{opt} thus achieves efficient use of resources, one of the goals of EBFM (Brodziak and Link, 2002).

Of the examined species, at least Cod is known to be cannibalistic (Daan, 1973). Thus, rebuilding a large biomass of large Cod under the L_{opt} scenario is likely to result in increased predation on juvenile Cod. However, because spawning stock size as well as mean size and age are largest under this scenario, recruitment is likely to be higher and more stable than under the other scenarios (Myers and Barrowman, 1996; Hsieh et al., 2006), and is likely to more than compensate for effects of cannibalism. Also, large Cod will consume substantial amounts of other commercial species (Daan, 1973). Modelling the effects of such changes in size structure with available ecosystem models is possible but not trivial and therefore not readily available (Villy Christensen, Fisheries Centre, UBC, personal communication, 2007). The overall results of such exercise may be anticipated

from the fact that in historical times when biomass of large Cod was much higher than today, other commercial species also had substantially higher biomasses (Lotze, 2004; Roberts, 2007).

We also present our results in the framework of relative yield and biomass per recruit isopleth diagrams, which will be familiar to fisheries managers. Beverton and Holt (1957) present a version of this diagram with "eumetric" lines designating the area where yield is maximum for a certain fishing mortality or mean age at first capture, as a target area for fisheries managers. Here we present new versions of these diagrams which take account of the need to minimize impact of fishing on biomass and size structure of the population for precautionary and ecosystem purposes, resulting in a new target area for fisheries managers.

Traditional fisheries management such as proposed by the European Commission (2006a,b) aims for reducing effort and shifting fisheries towards the left side of the yield and biomass per recruit graphs (Figs. 5 and 6), lowering exploitation rate without changing size at first capture (lower arrow). Note that in the mid-left section of Fig. 5, yield per recruit isopleths are nearly vertical, thus supporting the widespread notion of fisheries managers that size does not matter for yield if effort is reduced. However, as shown by the dashed line in Fig. 2 and the isopleths in Fig. 6, such fishing severely truncates the size and age structure and strongly reduces cohort biomass. Truncation of age structure has been suggested as the main reason for the observed higher variability in abundance of exploited species (Hsieh et al., 2006). Also, such fishing kills more fishes than needed to obtain a certain catch (Fig. 1). Thus, precautionary management and ecosystem-based management both call for fishing in the upper left section of the graph, around the L_{opt} line (upper arrow). Note that relative yield per recruit is about the same for the three scenarios. However, over time we would expect more recruits and thus larger catches under the L_{opt} scenario.

We also explored presenting our results in the framework of a biomass per recruit isopleth diagram. This approach was widely used in the past but seems to have been almost forgotten, with inappropriate equations mentioned in several manuals of stock assessment. We went back to the original formulation (Beverton and Holt, 1957) and derived what we believe is the first explicit equation for relative recruited biomass per recruit based on length parameters. Like for yield, we show a generic diagram suitable for simultaneous presentation of different stocks (Figs. 5B and 6B). This gives a good overview on the impact of various management strategies that could be applied. We particularly show that the current regime is responsible for a strong biomass reduction, especially for demersals, while the proposed fishing at L_{opt} would greatly increase both abundances and yields.

For small pelagics the mean yield per recruit diagram tells a somewhat different story (Fig. 6). In all stocks size at first maturity and size at first capture are close to L_{opt} and exploitation rates are lower than for ground fish, suggesting a more sustainable current management of these species. However, North Sea Herring has been overfished in the past and stock size is currently decreasing due to recruitment failures since 2001 (ICES Advice 2007, www.ices.dk/advice/icesadvice.asp). Increasing size and

age at first capture will allow more fish to spawn in several years, thus increasing their chances to overcome periods of recruitment failure.

In the Baltic, fisheries are mostly single-species with little by-catch and thus implementation by increasing mesh sizes seems straightforward. Increased mesh sizes will reduce fishing mortality and exploitation rate, and a well-timed step-wise introduction may allow reaching the L_{opt}-scenario without drastic reduction in catches in the transition period and higher catches in the long term. Existing subsidies could be redirected to compensate fishers for economic losses during such period. In the North Sea most trawl fisheries are multi-species fisheries with considerable by-catch, a management problem that has to be addressed anyway, either through different gears and fishing patterns or by managing for the largest species, which in the case of Cod is also the economically most important one. Other examples where L_{opt} management has been successful are discussed below.

We want to stress that the EC-MSY scenario of fishing 'forage' species as well as top predator species at MSY levels may not be realistic and that species interactions have to be taken into account, e.g., by reducing fishing mortality on prey species (Walters et al., 2004) and increasing minimum sizes towards L_{opt}. Still the proposed EC-MSY fishing scenario is a significant improvement compared to the current fishing scenario. However, there is substantial scope for additional improvements towards the goals of precautionary and ecosystem-based fisheries management if size at first capture is increased. In summary, an L_{opt} fishing regime has the following advantages:

1. Age and size structure as well as biomass of the fished populations better resemble those of unfished ones, thus achieving a major goal of EBFM: juveniles and first-time spawners are left untouched, and impact on large spawners is minimized. These specimens can now fulfil their respective ecosystem functions as prey or predators (Christensen, 1996; Pauly et al., 1998).
2. All fish are given a chance to reach the size of maximum growth rate ($L_{opt} \sim$ length where dW/dt is maximum) and reproduce before being caught, so growth and recruitment overfishing is theoretically impossible (Myers and Mertz, 1998) and impact on expected life-time fecundity per recruit (Goodyear, 1993) is reduced.
3. Starting fishing at large size results in substantial survival of large and potentially late spawners, so unnatural selection pressures towards smaller size, earlier maturation and shorter lifespan (Conover and Munch, 2002; Ernande et al., 2003; Birkeland and Dayton, 2005) is minimized and resilience to extended periods of recruitment failure due to environmental conditions is increased (Longhurst, 2002).
4. New cohorts are left unfished for quite some time, which facilitates stock assessment and reliable estimation of allowable catches, rather than depending on much less reliable surveys of eggs, larvae or juveniles combined with various assumptions.
5. Because recruits are not fished for several years and because mean age and length and diversity of age structure are increased, the influence of recruitment on the size of the stock

is diminished (Myers and Barrowman, 1996; Secor, 2000; Hsieh et al., 2006). This supports stable annual catches, a major demand of the fishing industry.

6. Assuming that gears and fishing patterns will be used that select for large specimens near L_{opt}, by-catch and discard of smaller specimens and species will be drastically reduced, a major goal of EBFM.

7. Cohort and stock biomass is several-fold higher, thus increasing catch per unit effort and reducing cost of fishing. Alternatively, if less efficient gears and fishing patterns were needed to avoid by-catch and only target fish after L_{opt}, this additional cost may be compensated by higher catch per effort.

8. In summary, L_{opt}-fishing will result in biomasses and age-structures of target and by-catch species that will be closer to the unexploited state. This will improve ecosystem resilience and stability as preconditions for reliable ecosystem services.

If the L_{opt} fishing scenario has so many advantages, why is it not done? Well, it is done elsewhere. For example, Jackson et al. (2001) point out that many collapsed stocks have not yet recovered, in some cases even 100 years after their initial collapse. One prominent exception to that rule is the Chesapeake Bay Striped Bass (*Morone saxatilis*: Moronidae), for which, after a severe decline due to recruitment overfishing during the 1980s, a management plan was adopted which set the minimum harvest length where 95% of females had spawned at least once, a size close to L_{opt}. This increased the age at entry to the fishery from 2 to 8 years (Richards et al., 1994). The stock was declared fully recovered in 1995 and is currently undergoing Marine Stewardship Council (MSC) certification assessment for sustainability.

Another example is the Gulf of Alaska Pollock (*Theragra chalcogramma*: Gadidae) shown in Fig. 7. Fishing starts after first spawning and the amount taken is 26% of the unfished cohort biomass at L_{opt}. There is no impact on juveniles or first-time spawners and only very modest impact on large adults. Additionally, mesh sizes and fishing methods are used such that there is extremely little discarding and by-catch in this fishery (less than 1% by weight) (Alverson et al., 1994). This is a productive and well-managed fishery that was certified as sustainably harvested by the MSC in April, 2005 (www.msc.org/html/content_492.htm). A similar management regime is used for the Bering Sea stock of this species, which is one of the most productive fisheries in the world, yielding 1.5 million tonnes in 2004 (Ianelli et al., 2005) and which was MSC certified in 2005 (www.msc.org/html/content_1176.htm).

In summary, in many fisheries, considerably more damage is done to the respective stocks and ecosystems than is necessary to obtain current catches. This is caused by management focusing on effort reduction while targeting fishes well below size at first maturity and size where impact on cohorts is minimum. Shifting target sizes towards L_{opt} will, in most cases, allow current catch levels to be regained or exceeded after a short transition period while at the same time rebuilding stocks and minimizing impact on the ecosystem. Additionally, applying this management approach does not require many difficult-to-enforce regulations as has been cited as a barrier to adopting some EBFM strategies (Brodziak and Link, 2002; Froese, 2004). Examples such as the Alaska Pollock fishery show that this is not an unrealistic scenario. The proposed new EC-MSY management regime is a step in the right direction, but would benefit greatly if it were to include incentives for L_{opt} as target size. Our new interpretation of the classic yield-isopleth diagram (Beverton and Holt, 1957) in an EBFM framework reveals a new target area for fisheries managers and shows how precautionary single-species management can substantially contribute to ecosystem-based fisheries management without drastic reduction in catches. A new version of the relative biomass per recruit isopleth diagram supports these findings.

Acknowledgements

Appendix A. Calculation of yield and biomass per recruit

Yield per recruit (Y/R) is defined as the mean catch that a recruit provides. It may be estimated from the sum of catches over all the exploited phase of a cohort as:

$$\frac{Y}{R} = \frac{1}{R} \int_{t_c}^{\infty} F N_t W_t \, dt \tag{A1}$$

where F is the fishing mortality occurring during all the exploited phase, N_t and W_t are the number and the mean weight at age t.

According to Beverton and Holt (1957) and Ricker (1975), integration of (A1) is equal to:

$$\frac{Y}{R} = F W_\infty e^{-M(t_c - t_r)} \sum_{n=0}^{3} \Omega_n \frac{e^{-nK(t_c - t_0)}}{F + M + nK} \tag{A2}$$

where W_∞, K, t_0 are the parameters of the VBGF; t_c and t_r are, respectively, the age of first catch and the age of recruitment; and $\Omega_n = 1, -3, 3$ and -1 for $n = 0, 1, 2$ and 3, respectively.

From this, an expression of the "relative" yield per recruit may be deduced, using length in place of age (Beverton and Holt, 1966):

$$\frac{Y'}{R} = E \left(1 - \frac{L_c}{L_\infty}\right)^{M/K} \sum_{n=0}^{3} \Omega_n \frac{(1 - L_c/L_\infty)^n}{1 + n(1 - E)/(M/K)} \tag{A3}$$

where $Y/R = Y'/R \, W_\infty e^{-M(t_r - t_0)}$; $E = F/(F + M)$ is the exploitation rate and L_c is the mean length at first capture.

Eq. (A3) allows us to calculate Y'/R as a function of the three parameters L_c/L_∞, E and M/K and to calculate the related isopleths of relative yield per recruit.

Relative biomass per recruit is usually defined as the ratio $(Y'/R)/(F)$ (e.g., Cadima, 2003). According to Eq. (A1), this ratio

only refers to the exploited phase; for a given F, it decreases when t_c increases, because a smaller portion of the stock is exploited. But at the same time a larger portion of the stock is protected from fishing, leading to an increase in the total stock biomass. In other words, this ratio is proportional to the CPUE but it cannot be used to measure the effect of various scenarios of fishing on the stock abundance. For such a purpose, we used a biomass per recruit equation related to the total stock (i.e., the recruited phase) as follows:

$$\frac{B}{R} = \frac{1}{R} \int_{t=t_r}^{\infty} N_t W_t \, dt = \frac{1}{R} \int_{t=t_r}^{t_c} N_t W_t \, dt + \frac{1}{R} \int_{t=t_c}^{\infty} N_t W_t \, dt \tag{A4}$$

The second term of Eq. (A4) is already known as $(Y/R)/(F)$, see (A1). Conversely, the first term, related to the cumulative biomass of the cohort between t_r and t_c, has to be calculated. According to Beverton and Holt (1957), integration of (A4) leads to:

$$\frac{B}{R} = W_{\infty} \sum_{n=0}^{3} \Omega_n \frac{e^{-nK(t_r-t_o)}}{M+nK} [1 - e^{-(M+nK)(t_c-t_r)}] + \frac{Y/R}{F} \tag{A5}$$

We found in the literature no expression of (A5) converted to length, as presented above in the case of yield per recruit. With algebraic transformations of (A5) we obtain:

$$\frac{B}{R} = W_{\infty} \sum_{n=0}^{3} \Omega_n \left[\frac{e^{-nK(t_r-t_o)} - e^{-M(t_c-t_r)-nK(t_c-t_o)}}{M+nK} \right.$$

$$\left. + \frac{e^{-M(t_c-t_r)-nK(t_c-t_o)}}{M+F+nK} \right] = W_{\infty} \sum_{n=0}^{3} \frac{\Omega_n}{M+nK}$$

$$\times \left[e^{-nK(t_r-t_o)} - e^{-M(t_c-t_o)-M(t_o-t_r)-nK(t_c-t_o)} \right.$$

$$\left. \times \left(1 - \frac{M+nK}{M+F+nK} \right) \right] = W_{\infty} \sum_{n=0}^{3} \frac{\Omega_n}{M+nK}$$

$$\times \left[\left(1 - \frac{L_r}{L_{\infty}} \right)^n - \left(1 - \frac{L_c}{L_{\infty}} \right)^{M/K+n} \left(1 - \frac{L_r}{L_{\infty}} \right)^{-M/K} \right.$$

$$\left. \times \frac{E}{1+n(1-E)/(M/K)} \right] \tag{A6}$$

The relative biomass per recruit is then defined as:

$$\frac{B'}{R} = \frac{B/R}{(B/R)_v} \tag{A7}$$

where $(B/R)_v$ is the biomass per recruit calculated for an unexploited stock with $F = 0$.

Substituting (A6) into (A7) we finally obtain:

$$\frac{B'}{R} = \frac{\sum_{n=0}^{3}(\Omega_n/(M+nK))[(1-L_r/L_{\infty})^n - (1-L_r/L_{\infty})^{M/K+n}(1-L_r/L_{\infty})^{-M/K} \times (E/(1+n(1-E)/(M/K)))]}{\sum_{n=0}^{3}(\Omega_n/(M+nK))(1-L_r/L_{\infty})^n} \tag{A8}$$

This relative biomass per recruit B'/R varies from 1 (no fishing) to 0 (stock extinct) and is an index of the abundance of the stock. Conversely to Eq. (A5), Eq. (A8) does not include the parameters t_0 and W_{∞}. Thus, relative biomass per recruit can be calculated as a function of the three parameters M/K, E and L_c/L_{∞}. However, this biomass index includes two additional parameters, the L_r/L_{∞} ratio and natural mortality M. For the purpose of showing several stocks in one B'/R graph, we considered a unique age $t_r = 1$ for all stocks. B'/R thus refers to biomass of all fishes older than 1 year. In order to obtain a common diagnosis for the various stocks, we built two graphs of mean B'/R isopleths, one for demersals and the other for pelagics. We used mean values for M (0.21 and 0.43 for demersals and pelagics, respectively, from Table 2) and for L_r/L_{∞} (0.22 and 0.50, based on VBGF parameters from Table 2 and Eq. (1) applied to age 1).

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